Influence of African dust on tropical Atlantic coupled variability

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The Atlantic Meridional Mode is the dominant source of coupled atmosphere–ocean variability in the tropical Atlantic, characterized by a hemispheric sea surface temperature gradient and cross equatorial surface winds that reinforce ocean temperature anomalies in both hemispheres[1–4]. The Atlantic Meridional Mode is thermodynamically damped and requires external forcing to persist as is observed[3]. However, there is not consensus regarding the external forcings that have excited the AMM in the historical record, and thus govern regional coupled climate variability[4]. Here we use observations and a physical model to show that the Atlantic Meridional Mode is excited by variability in African dust outbreaks via the dust radiatively-forced SST anomalies on interannual to decadal time scales. Our analysis suggests that SST anomalies resulting from the aerosol direct effect persist in time via the wind-evaporation-sea surface temperature feedback[5] that defines the Atlantic Meridional Mode[1–3]. We conclude that on interannual to decadal time scales the state of the tropical Atlantic is directly tied to land surface processes over West Africa via dust emission. These results suggest that human activity may already be altering regional climate via land use change[6–8].

West Africa is the largest global source of atmospheric dust due to an abundance of deflatable materials and strong seasonally varying low-level winds[9], and the majority of dust generated in West Africa is advected over the tropical and subtropical North Atlantic[10]. Mineral aerosols have a high single scatter albedo and over dark surfaces the scattering of sunlight dominates absorption of infrared radiation such that the net effect at the surface is a reduction in downwelling radiation[11]. To first order such a reduction in the surface heat flux cools the ocean mixed layer[12–14], and since the mid 1980s a decrease in Atlantic dust optical depth[11,15] (Fig 1) has resulted in an increase in the amount of solar radiation absorbed at the ocean surface[14] and a small upward trend in tropical North Atlantic sea surface temperature (SST)[12]. Between 1955 and 1985 there was a pronounced increase in dust optical depth over the tropical North Atlantic[7,11] (Fig 1), in turn cooling SST here[7].

To investigate the impact of DAOD variability on regional climate we first estimate the effect of dust on tropical North Atlantic SST by forcing a version of the Massachusetts Institute of Technology Ocean General Circulation Model[16,17] with a dust radiative forcing climatology that covers the period 1955–2008[11]. The change in SST from anomalous dust optical depth is obtained by differencing model output from a 54-year run that is forced only by seasonally varying surface heat fluxes from an atmospheric reanalysis[18], and a separate run in which the monthly fluxes also include the historical contribution to the surface radiative flux by anomalous dust optical depth. We are estimating the effect of dust on Atlantic SST about the climatological mean state, thus from the model experiments periods of anomalously high dust force SST cool anomalies while periods of anomalously low dust loading force SST warm anomalies (see Methods).

The spatial structure of the sensitivity of tropical Atlantic SST to changes in dust is estimated via a composite difference of modeled SST during the five most (1983–1988) and least (1956–1958, 2004, 2005) dusty years (Fig 1). The dust forced SST (hereafter ΔSST) composite reaches a maximum of 0.3°C over a broad region centered on 25°W and 20°N, decays to zero near the equator and slightly north of 30°N, and exhibits a weaker gradient to the west of the cool maximum. The spatial structure of the *ΔSST* composite is very similar to that of the Atlantic Meridional Mode (AMM) (Fig 1). The AMM structure is estimated via a Maximum Covariance Analysis of tropical Atlantic SST and reanalysis 10-*m* winds over the domain 21°S–32°N and 74°W to the West African coastline[2]. The asymmetric structure of the AMM reflects the meridional gradient feature of the AMM, and the wind-evaporation-SST (WES) feedback, the destabilizing mechanism for transient growth of the AMM[3,5,19]. The WES feedback is the tendency of surface winds to blow from the cool to the warm hemisphere and reduce (increase) evaporation in the warm (cool) hemisphere via a net weakening (enhancement) of the climatological easterlies, thereby reinforcing the existing SST gradient[3,5].

Through the WES feedback, the AMM is strongly influenced by the underlying SST. Therefore, the similarity in the spatial structures of the AMM and *ΔSST* suggests that dust radiative forcing may excite coupled variability of the equatorial Atlantic. To demonstrate the mechanics of such a process we consider the coupled response to dust-like radiative forcing in the idealized coupled equatorial model[3]:

$$\frac{\partial}{\partial t}\begin{pmatrix} u \\ v \\ h \\ T \end{pmatrix} = \begin{pmatrix} -\epsilon_u & \beta y & -g'\partial/\partial x & \Gamma_{RG}\partial/\partial x \\ -\beta y & -\epsilon_u & -g'\partial/\partial y & \Gamma_{RG}\partial/\partial y \\ -H_b\partial/\partial x & -H_b\partial/\partial y & -\epsilon_M(y) & 0 \\ \alpha(y) & 0 & 0 & -\epsilon_T + \gamma\nabla^2 \end{pmatrix}\begin{pmatrix} u \\ v \\ h \\ T \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ F_{dust} \end{pmatrix} \quad (1)$$

where the left-hand side of (1) are the time tendencies of the zonal (u) and meridional (v) winds, perturbation boundary layer height (h), and SST (T). The right hand side of (1) consists of the dynamical system matrix (4x4 matrix) and a forcing vector indicating possible SST forcing from dust (F_{dust}). The upper-left 3x3 matrix of the dynamical system matrix are the reduced gravity (g') shallow water equations on an equatorial beta plane linearized about a state of rest[20], with linear dampening terms along the main diagonal; these represent a tropical atmospheric boundary layer of depth H_b. The atmospheric boundary layer is coupled to a slab ocean via SST-induced hydrostatic pressure perturbations ($\Gamma_{RG}T$). The ocean is coupled to the atmosphere via the WES term (α) such that model growth occurs when u and T anomalies are in phase. T anomalies are damped via the linear and harmonic dampening term, in the lower right-hand corner of the 4x4 matrix. All coefficients have the same values as in Vimont[3]. A parameterized dust forcing can be applied to the model via the right-most vector in (1). Though a simplified version of the real atmosphere, the model in (1) provides a useful theoretical framework for understanding the response of the coupled tropical system to an idealized forcing.

From the unforced version of (1) the AMM emerges both as the structure exhibiting the maximum transient growth, and a steady response to "optimal forcing" anomalies (Vimont, 2010). To examine the theoretical coupled response to dust-like forcing we impose a forcing term F_{dust} in the SST tendency equation (1) with a spatial structure similar to that from our model experiment (ΔSST, Fig. 1), i.e., zonal and meridional scales of 60° longitude and 30° latitude and centered at 20°N (Fig. 1); note that the model is harmonic in the zonal direction. The model is integrated forward for one year, forced with this idealized heating term for the first four months of the model integration, reflecting the typical time scale of anomalous forcing of SST by dust[11]. During the remaining 8 months, the model solution evolves via the internal coupled dynamics in the homogeneous version of (1).

During months one through four, when the dust heating term is applied, the monthly mean maps of the coupled model SST, surface wind, and boundary layer pressure fields show an equatorward and westward migration of SST anomalies outside of the original forcing region, which are forced by the anomalous westerlies (easterlies) on the equatorward side of the negative (positive) geopotential anomaly that overlies the warm (cool) SST anomaly (Fig. 2). Starting in month four there is an SST anomaly in the southern hemisphere that is opposite in sign to the imposed forcing. This SST signal is the response to the anomalous cross-equatorial flow, and it continues to amplify via coupled dynamical processes for several months after the imposed forcing is turned off (Fig S5). At model month eight, four months after the imposed heating is turned off, there still exists a meridionally asymmetric SST anomaly accompanying the cross-equatorial winds, and this pattern persists through the model integration (Fig S5).

The similarity between the spatial structure of the AMM and ΔSST (Fig. 1) and the result from our idealized model experiments (Fig. 2) suggest there may be a coupled equatorial response to Atlantic dust outbreaks in nature. We next investigate the relative importance of such dust-forced variability on interannual to decadal time scales by comparing the time series of the observed AMM with the component of the observed AMM we estimate to be directly forced by dust. We first recover the observed AMM time series (AMM_{obs}) by projecting maps of observed SST anomalies[22] onto the stationary spatial pattern of the AMM (Fig 1) ($AMM_{x,y}$), and then normalize the resultant time series to a mean of zero and standard deviation of one,

$$AMM_{obs}(t = t_0) = \frac{SST'(t = t_0) \times AMM_{x,y}}{\sigma_{AMM(t)}}. \tag{2}$$

The left-hand side of (2) indicates the value of AMM_{obs} at time t_0, the prime indicates monthly anomalies of SST also at time t_0, and $\sigma_{AMM(t)}$ is the standard deviation of the product in the numerator for all t (Fig 2). We note that the SST anomalies have been detrended and SST variability associated with ENSO has been removed by regressing out the monthly Nino 3.4 index at each point (although excluding the ENSO regression step gives a very similar result). We similarly estimate the dust-forced component of the AMM (AMM_{dust}) by calculating the magnitude of the projection of monthly mean ΔSST onto $AMM_{x,y}$,

$$AMM_{dust}(t = t_0) = \frac{\Delta SST(t = t_0) \times AMM_{x,y}}{\sigma_{AMM(t)}}, \tag{3}$$

where the left-hand side of (3) indicates the value of AMM_{dust} at time t_0 and ΔSST is used in place of SST' in (2). The normalization coefficients are the same for AMM_{obs} and AMM_{dust}, thus the magnitudes of the two time series are comparable.

AMM_{obs} exhibits both interannual and decadal scale variability[1,2,19], with coherent periods of positive and negative values during each decade (1) (Fig 3a). AMM_{dust} contains longer periods of coherent positive and negative values, with mostly positive values during the beginning and end of the record, and mostly negative values in the middle of the time series, consistent with historical estimates of regional dustiness[7,11,15] (Fig 3b). AMM_{dust} anomalies are of a similar magnitude to AMM_{obs}. The range of annual mean AMM_{obs} and AMM_{dust} is 5.32 and 3.02 units standard deviation, respectively, and the standard deviation of AMM_{dust} is 0.67 (that of AMM_{obs} is by definition unity). The magnitude and standard deviation of 5-year low pass filtered AMM_{obs} and AMM_{dust} anomalies (Fig. 3C) are nearly equal, suggesting that dust forcing is an important component of observed coupled variability on decadal time scales.

Based on our idealized coupled model experiments (Fig. 2) and given time scales of the WES feedback[3,5] we expect growth of any dust (radiatively) forced AMM anomaly over a finite period. SST forcing by dust should excite a zonal wind anomaly that reinforces and grows the initial radiatively-forced anomaly. The cross-correlation function of the unfiltered and five year low pass filtered AMM_{obs} and AMM_{dust} are a maximum (0.34 and 0.57, respectively) when the dust forced component leads the AMM by two years, both statistically significant at the 95% level based on a 1000-sample permutation test (Fig S6). The positive correlation when AMM_{dust} leads AMM_{obs} suggests that the integrated effect of anomalous dust surface radiative forcing and the WES feedback conspire to amplify the response of the coupled mode to anomalous dust optical depth. Given the time scales of meridional mode growth[3] we expect the cross-correlation function to be a maximum when AMM_{dust} leads AMM_{obs} by one year, not the two years shown in our analysis (Fig S6). We speculate the discrepancy is related to uncertainty in the seasonality of the radiative forcing from our annual dust reconstruction, and our use of uncoupled model experiments for estimating the spatial and temporary characteristics of ΔSST, although the neglect of slow ocean processes in the coupled model may also be relevant.

Historical variability of the AMM may have been externally forced by the NAO and ENSO[23], and AMO[24], or emerged from random variability[1]. Historical dust emission is a function of surface processes and local to synoptic scale meteorological conditions[7,9,10,15], and transport is related to the phase of the North Atlantic Oscillation[25] and ENSO[26]. We suggest that dust variability contributes to observed AMM variability via the coupled mechanisms described here. Our finding that solar radiation forces a significant portion of the observed tropical Atlantic SST variability is consistent with a tropical Atlantic surface heat budget analysis[27] and additional model experiments examining the relative contributions of latent heat and solar radiation fluxes to long-term variability of the AMM (See Supplement).

Since tropical Atlantic environmental conditions are more favorable for hurricane genesis and intensification when the AMM is in a positive phase[24,28], the negative correlation between Atlantic dustiness and hurricane activity[29,30] may be the result of forcing of the AMM by anomalous dust outbreaks. In addition, anthropogenic land use has played a role in augmenting African dust emissions, although by what amount is uncertain[6–8]. Thus the possibility exists that human activity may have already been altering regional climate through the dust-ocean-atmosphere interactions shown here. Furthermore, in the future carbon dioxide fertilization may lead to shrinking desert areas and a reduction in African dust outbreaks[6], and therefore more favorable conditions for hurricanes to form and intensify via anomalous dust-forcing of the AMM.

Methods

The dust climatology[11] is based on a reconstructed time series of dust optical depth over Cape Verde that utilizes a coral proxy record (1955–1994) and satellite retrievals (1982–2008). African dust outbreaks are advected over the Atlantic at the latitude of Cape Verde throughout the year[10], and as such dust optical depth over the tropical North Atlantic is well-correlated to dust at Cape Verde on monthly to interannual time scales[11]. Additionally, a comparison of the dust time series used here with a slightly shorter series made from in-situ measurements at Barbados[15] shows a very high level of agreement on interannual to decadal time scales (Fig S1). Additional details regarding the forcing and dust optical depth climatology are in Evan and Mukhopadhyay[11]. A global version of the Massachusetts Institute of Technology Ocean General Circulation Model[16,17] is spun up to a steady state with climatological monthly surface horizontal momentum fluxes and surface heat fluxes calculated offline using the National Centers for Environmental Protection Reanalysis[18]. We performed two separate model runs, each initialized from a 150 year spinup run. For the control run we continue forward the climatology forcing for an additional 54 years, for the perturbation run we subtract from the surface heat flux climatology the monthly mean contribution from anomalous dust variability. The dust contribution to the surface heat flux is defined as the monthly dust aerosol direct effect at the surface minus the annual cycle. The difference between the control and perturbation runs is considered to be the effect of departures in dustiness from the seasonal mean. Additional details on the model configuration can be found in the supplemental material.

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Acknowledgements

Funding for this work was provided by NOAA/CLIVAR grants NA10OAR4310136 and NA10OAR4310207.

Author Contributions

A.T.E. and D.J.V. designed and performed the model experiments; A.T.E, G.R.F., D.J.V. and D.Z. analyzed and interpreted the model output and co-wrote the paper.

Figures

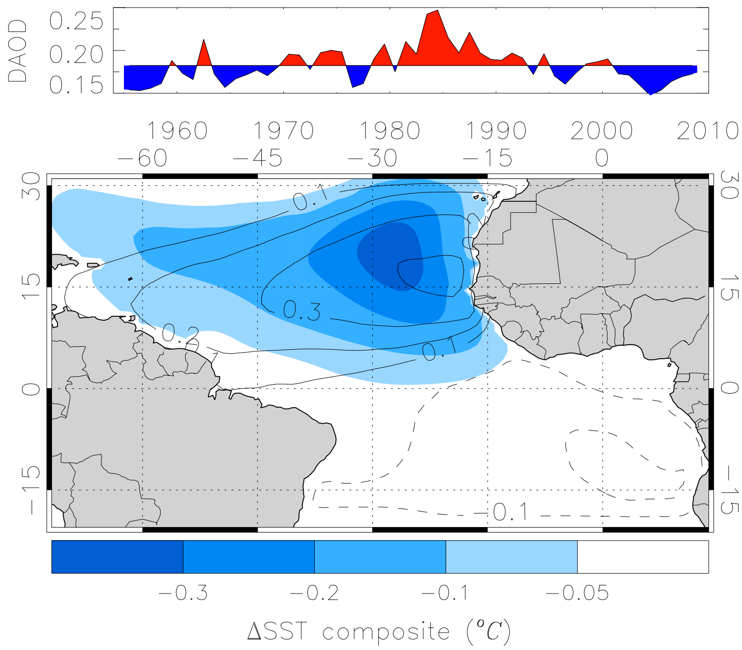

Figure 1. Time series of dust optical depth, footprint of dust on tropical Atlantic SST, and the spatial pattern of the AMM. Plotted is the annual time series of dust optical depth (DAOD)[16] averaged over the region 10-20°N and 20°-50°W (top). Dust optical depth is a measure of the extinction of light through the dust layer and is proportional to mass concentration. In the map are contours of the spatial pattern of the AMM ($AMM_{x,y}$), defined as the regression of SST (℃) onto the leading mode of a maximum covariance analysis applied to reanalysis SST and lower-level winds over the domain 19°S–30.5°N and 71°W–13°E[2]. Shading denotes composite differences of ΔSST and demonstrates the similarity between the AMM spatial pattern and the SST pattern forced by changes in dust optical depth.

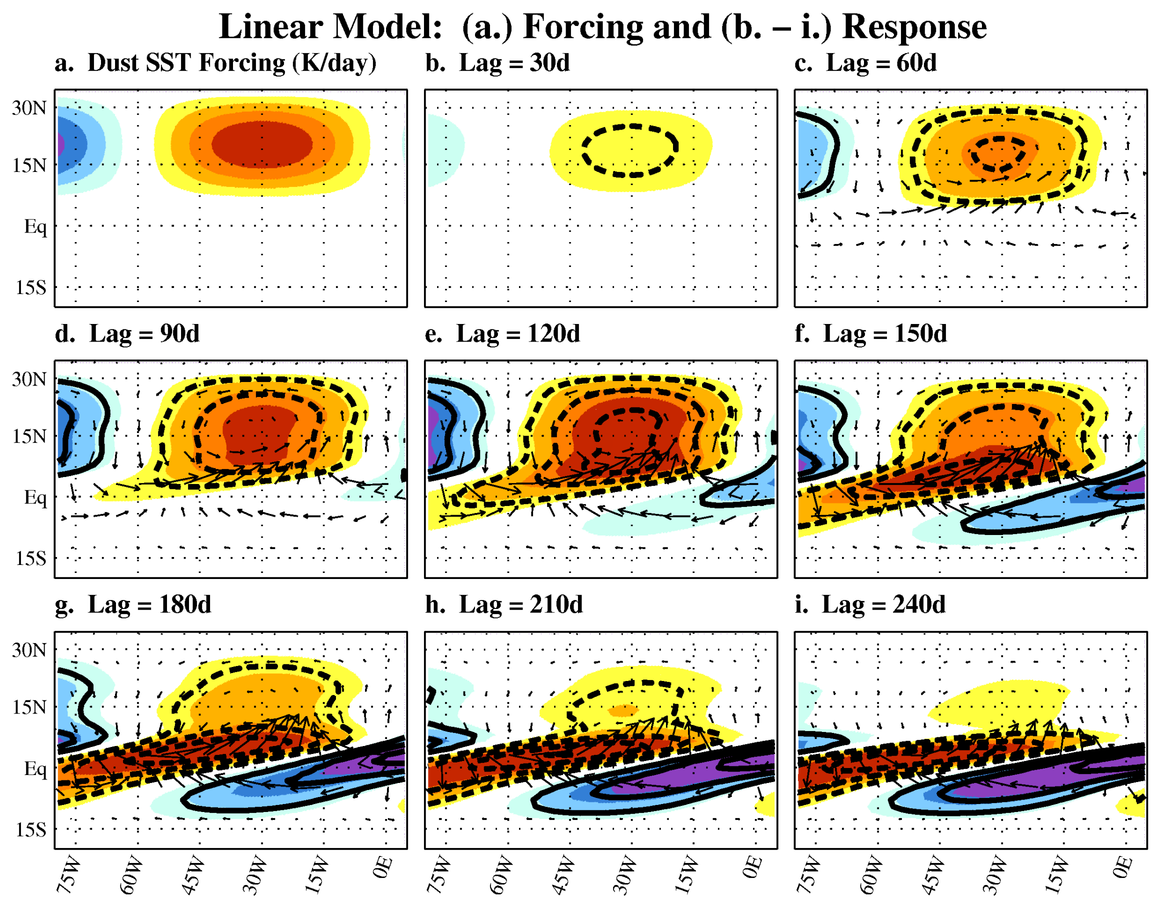

Figure 2. Monthly mean output from idealized coupled model experiments. The top left panel (a.) depicts the idealized dust forcing (K day^{-1}) used to force the coupled model during the first four months. The remaining panels (b. – i.) show the equatorward and westward evolution of the model response in monthly mean SST (shaded), boundary layer pressure (contours), and boundary layer winds (vectors) for model months 1-8. Positive (negative) SST anomalies are shaded red (blue) and positive (negative) pressure anomalies are drawn with solid (dashed) contours and the zero line has been omitted. Units are arbitrary but consistent throughout panels (b.) – (i.) so amplitudes may be compared. For reference, a 5 W m^{-2} forcing in panel

(a.) would produce a maximum warming of about 0.2 K in four months (panel e.).

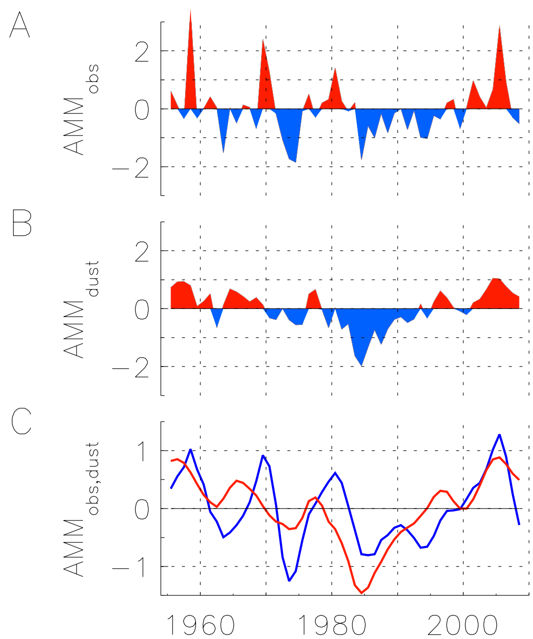

Figure 3. Observed and dust-forced component of the AMM time series. Plotted are annually averaged observed AMM time series (A), annually averaged dust-forced component of the AMM (B), and the 5-year low-pass filtered AMM_{obs} (blue) and AMM_{dust} (red) time series (C). As both time series have the same normalization, similarity between AMM_{obs} and AMM_{dust} indicates the magnitude of direct forcing of the AMM by African dust outbreaks.